# Staff Summary Sheet

| | To | Action | Signature (Surname), Grade, Date | | To | Action | Signature (Surname), Grade, Date |
|---|---|---|---|---|---|---|---|
| 1 | DFEM | Approve | G-6, 3APR13 | 6 | | | |
| 2 | DFER | Review | Kraus, Col 4Apr13 | 7 | add distribution statement to all Tabs | | |
| 3 | DFEM | Action | | 8 | | | |
| 4 | | | | 9 | | | |
| 5 | | | | 10 | | | |

| Grade and Surname of Action Officer | Symbol | Phone | Suspense Date |
|---|---|---|---|
| Capt Joseph Wahlquist | DFEM | 333-8553 | |

| Subject | SSS Date |
|---|---|
| Clearance of Material for Public Release Case Number: To be Assigned USAFA-DF-PA-280 | 2 Apr 2013 |

**Summary**

**1. Purpose**: To provide security and policy review on the documents at Tab 1 prior to release to the public.

**2. Background**:

- *Presentation and Supporting Material:* Innovative Solutions Against Hard and Deeply Buried Targets

- *Release information*: National Security Innovation Competition (NSIC), 26 Apr 13

Association for Unmanned Vehicle Systems International conference (AUVSI), 12-15 Aug 13

- *Previous clearance information*: N/A

- *Recommended distribution statement*: Distribution A, Approved for public release, distribution unlimited.

**3. Discussion**: This research was performed by cadets enrolled in Mech Engr 491 & 492 – ~~Senior Capstone~~ Design under the direction of Capt Wahlquist and Dr. Jensen.

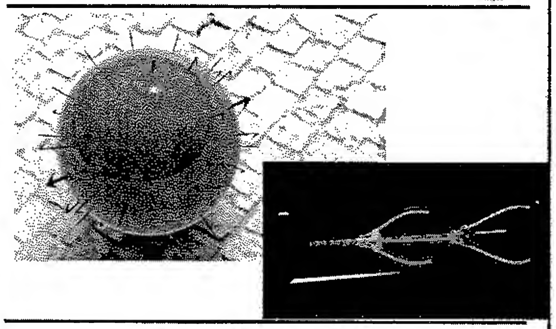
**4. Recommendation**: Sign coord block above indicating document is suitable for public release. Suitability is based solely on the document being unclassified, not jeopardizing DoD interests, and accurately portraying official policy.

Joseph Wahlquist

JOSPEH A. WAHLQUIST, Capt
Executive Officer and Assistant Professor
Department of Engineering Mechanics

4 Tabs
1. Presentation
2. Executive Summary
3. White Paper
4. Quad Chart


## Concepts Overview





## Pellet Overview

- Passive system to infiltrate HDBT
  - Hitch Ride (small hooks); attach to clothing/ equipment
- Launched from pneumatic launching system
- Detonation of tear gas
  - Timer/Remote
- Pellets can be can potentially be loaded with a variety of agents that can incapacitate enemy combatants



## Current Design

- Hollow Shell (ping pong ball)
  - Contains tear gas/explosive, igniter, receiver, circuitry
- Miniscule fishhooks
- Launch from paintball gun (pressurized gas)



## Pellet FMEA

| Description | Potential Failure Mode | Potential Effect of Failure | Root Causes | SEV | OCC | DET | RPN |
|---|---|---|---|---|---|---|---|
| Deployment | fails to reach target | no functional defeat | removed by bad guy | 8 | 5 | 2 | 20 |
| Deployment | mission compromised | no functional defeat | bad guy detects source | 8 | 5 | 4 | 10 |
| Deployment | Late ignition | functional defeat too late | timer set too late | 4 | 6 | 3 | 8 |
| Deployment | No ignition | no functional defeat | ignitor fails | 8 | 4 | 5 | 6 |
| Deployment | fails to reach target | no functional defeat | bad guy removes clothing | 4 | 3 | 2 | 6 |
| Deployment | fails to reach target | no functional defeat | hooks do not stick | 7 | 4 | 7 | 4 |
| Predeployment | fails to reach target | no functional defeat | unable to reach bad guy | 6 | 4 | 6 | 4 |
| Deployment | No ignition | no functional defeat | electronics fail | 8 | 2 | 5 | 3 |
| Predeployment | Preignition | friendly functional defeat | ignites early | 9 | 2 | 8 | 2 |
| Development | ineffective | no functional defeat | gas does not cause desired effect | 9 | 1 | 5 | 2 |
| Development | unable to carry | unable to reach target | too heavy | 10 | 1 | 10 | 1 |
| Development | unable to carry | unable to reach target | takes too much space | 10 | 1 | 10 | 1 |



## Pellet FMEA Top 3

| Potential Effect of Failure | Root Causes | SEV | OCC | DET | RPN |
|---|---|---|---|---|---|
| no functional defeat | removed by bad guy | 8 | 5 | 2 | 20 |
| no functional defeat | bad guy detects source | 8 | 5 | 4 | 10 |
| functional defeat too late | timer set too late | 4 | 6 | 3 | 8 |

## FMEA Pellet Testing

| Failure or performance mode | Approach: analytical, simulation or prototype test | Faculty who will sign off | Cadet(s) responsible | Due date |
|---|---|---|---|---|
| Hooks stick | Prototype Test- test if the hooks will stick on impact | Mr. Vincent | Dave | 31-Jan |
| Hard to remove | Prototype Test-pull to see if the hooks will fail | Capt Wahlquist | Kyle | 31-Jan |
| Proper Timing | Analytical- check our circuit/ timer to see if it will fail | EE Department | Davies | 31-Jan |
| Ignitor Works | Prototype Test- test igniter with capacitor and smoke chemicals | Capt Wahlquist | Davies/Tangeman | 31-Jan |
| Electronics Work | Analytical- verify analysis on electronics | EE Department | Dave | 31-Jan |
| Gas Effectiveness | Analytical- calculate the concentration of gas within a room with one ignition | Lt Col Buckley | Tangeman | 31-Jan |

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## Ignition System

- Created a smoke bomb using potassium nitrate and table sugar
- Inserted a rocket igniter
- Tested the ignition system

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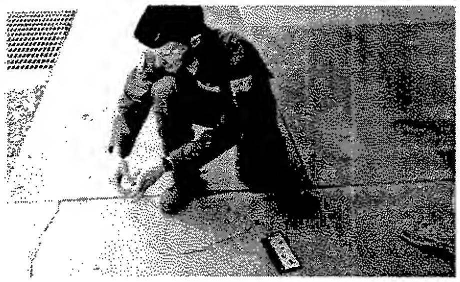
## Ignition System



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## Timing Circuit Components

- Digital Microcontroller
  - Low Power Unit
  - 1.8-3V, 1.1uA
- Transceiver
  - Low Power unit
  - 2.2-3.8V, 0.3uA

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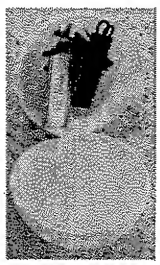
## Components Cont'd

- Electric igniter
  - ~70mA
- LiPo Battery
  - 30mAh capacity
  - Operation in standby mode – ~890 days
  - 750mA (25C) max discharge rate



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## Timing Circuit Overview

- First level: simple timer. Wait a predetermined time then light igniter. This level has been programmed but is not yet stand alone
- Second level: timer/receiver. First level plus wait until ignition transmitter comes in range then ignite immediately
- Third level: programmable. Second level plus timer is set wirelessly

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## Hooks

- Used ping pong balls
- Placed small holes throughout the halves
- Straightened out size 26 fish hooks and placed them in the holes
- Glued the hooks in place
- Added weights



## Drop Test

- Objective: Determine maximum impacting momentum of projectile
- Constraints: Target individual notices impact
- Analysis:
  - Paintball dropped on various body parts
    - Paintball = size/weight goal of final design
  - Max height without noticing was determined
  - Momentum on impact calculated
  - Launching momentum determined



## Drop Test Data

| Body Part | Height Dropped (m) | Impacting Momentum (kg-m/s) |
|---|---|---|
| Shoulder/Upper Back | 0.18 | 0.0056 |
| Lower Back | 0.30 | 0.0073 |
| Thigh | 0.30 | 0.0073 |
| Boot | 0.61 | 0.0104 |

- Result: Impact momentum is virtually the same as launching (paintball)



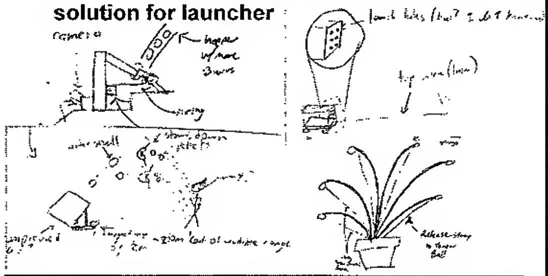
## Audio Thresholds

- According to Purdue University:
- Lowest limit of urban ambient sound:
  - 40 dB
- Quiet rural area
  - 30 dB
- Using these values, we made our goal to reach 40dB and our ideal launcher to be less than 30dB.



## Launching System

- Used 6-3-5 technique to develop innovative solution for launcher



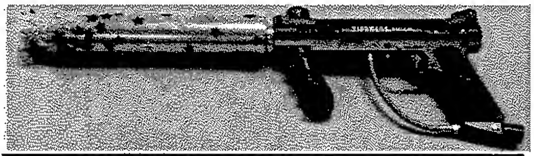


## Launcher Decision

| | Ease of build | Lauch Velocity Control | Noise Level | Visual Detectability | Repeatability | Accuracy | |
|---|---|---|---|---|---|---|---|
| | 8 | 6 | 5 | 2 | 3 | 6 | |
| Paintball Gun | 2 | 3 | -2 | 3 | 3 | 3 | 57 |
| Rail Gun | -3 | 3 | -3 | -1 | 1 | 2 | -8 |
| Low Pressure Gun | 0 | 3 | -1 | -1 | 3 | 3 | 38 |
| UAS | 0 | -2 | 3 | 2 | 2 | -3 | -5 |
| Pitching Machine | -1 | 2 | 1 | -1 | 3 | 2 | 28 |
| Spinning Launcher | -1 | 2 | 1 | -1 | 3 | 1 | 22 |
| Trebuche | 2 | 3 | 3 | -1 | 1 | 0 | 50 |
| Sling Shot | 2 | 2 | 2 | 1 | 2 | 2 | 58 |
| Spring Plant | 1 | 1 | 3 | 2 | 3 | -2 | 30 |
| Spring Launcher | 2 | 2 | 2 | 1 | 2 | 2 | 58 |
| Cross Bow | 1 | 2 | 2 | 2 | 1 | 1 | 43 |
| Passive Plant | 3 | 0 | 3 | 2 | -1 | -3 | 22 |

## Launcher Decision

- Top 3:
  - Paintball Launcher (57)
  - Spring Launcher (58)
  - Slingshot (58)
- Voted between group for final decision



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## FMEA After Analysis

| Description | Potential Failure Mode | Potential Effect of Failure | Root Causes | SEV | OCC | DET | RPN | New RPN |
|---|---|---|---|---|---|---|---|---|
| Deployment | fails to reach target | no functional defeat | removed by bad guy | 8 | 3 | 2 | 20 | |
| Deployment | mission compromised | no functional defeat | bad guy detects source | 8 | 5 | 4 | 10 | |
| Deployment | Late ignition | functional defeat too late | timer set too late | 4 | 4 | 3 | 8 | |
| Deployment | No ignition | no functional defeat | igniter fails | 8 | 2 | 5 | 6 | |
| Deployment | fails to reach target | no functional defeat | bad guy removes clothing | 4 | 3 | 2 | 6 | |
| Deployment | fails to reach target | no functional defeat | hooks do not stick | 7 | 2 | 7 | 4 | |
| Predeployment | fails to reach target | no functional defeat | unable to reach bad guy | 6 | 4 | 6 | 4 | |
| Deployment | No ignition | no functional defeat | electronics fail | 8 | 1 | 5 | 3 | |
| Predeployment | Preignition | friendly functional defeat | ignites early | 9 | 1 | 8 | 2 | |
| Development | ineffective | no functional defeat | gas does not cause desired effect | 9 | 1 | 3 | 3 | |
| Development | unable to carry | unable to reach target | too heavy | 10 | 1 | 10 | 1 | |
| Development | unable to carry | unable to reach target | takes too much space | 10 | 1 | 10 | 1 | |

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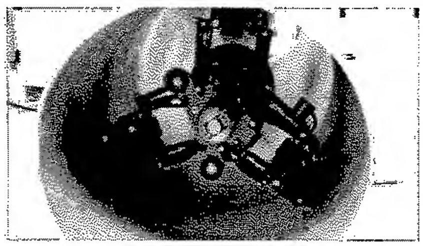
## Concept Overview

Original Concept - Sewer Tank



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## Sewer Tank from PDR

- Possible tank variant functions
  - Tank treads
    - Maneuver around obstacles
    - Infiltrate through sewage pipes or air ducts
  - Robotic multipurpose arm
    - Manipulate enemy systems
    - Place explosives
  - Storage unit
    - Store explosives and other attack equipment
  - Camera
    - Evaluate targets
    - Map enemy HDBT

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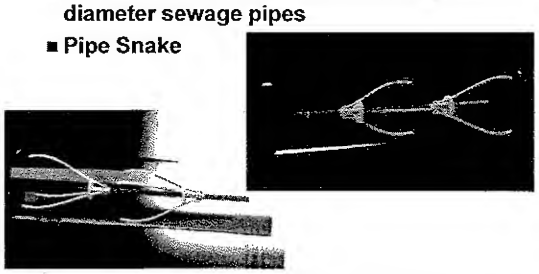
## Concept Modification

- Focus on innovative way to climb different diameter sewage pipes
- Pipe Snake



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## FMEA Pipe Snake

Failure Mode and Effects Analysis (FMEA) Worksheet

System, Product, or Process: Pipe Snake

| Background | | | | Rating | | | |
|---|---|---|---|---|---|---|---|
| Description | Potential Failure Mode | Potential Effect of Failure | Root Causes | SEV | OCC | DET | RPN |
| Deployment | fails to reach target | no surveillance/ no functional defeat | Unable to overcome obstacle | 8 | 6 | 4 | 12 |
| Deployment | fails to reach target | no surveillance/ no functional defeat | Batteries Die | 8 | 5 | 4 | 10 |
| Comm | Loses Comm | no surveillance/ control | Signal Strength not strong enough | 7 | 4 | 3 | 9.3 |
| Deployment | fails to reach target | no surveillance/ no functional defeat | Electronics fail | 9 | 3 | 3 | 9 |
| Deployment | fails to reach target | no surveillance/ no functional defeat | Discovered by enemy | 7 | 5 | 4 | 8.2 |
| Deployment | fails to reach target | no surveillance/ no functional defeat | Electronics short | 9 | 4 | 5 | 7.2 |
| Deployment | fails to reach target | no surveillance/ functional defeat | Treads Break | 9 | 2 | 3 | 6 |
| Deployment | fails to reach target | no surveillance/ functional defeat | Tread Falls off | 9 | 2 | 3 | 6 |
| View | Unable to see target | no functional defeat | Lens not focused on target | 4 | 3 | 2 | 6 |
| Deployment | fails to reach target | no surveillance | Sensors get covered | 7 | 3 | 4 | 5.9 |
| Predeployment | Lens Breaks | no surveillance | Rough Handling | 7 | 2 | 4 | 3.5 |
| Deployment | decrease in locomotion | delayed surveillance/ functional defeat | Supporting Wheel falls off | 5 | 2 | 5 | 2 |
| Deployment | fails to reach target | no surveillance/ no functional defeat | Transmission Slips | 4 | 2 | 8 | 1.3 |
| Deployment | fails to reach target | total failure | Body Breaks | 9 | 1 | 8 | 1.1 |
| Deployment | fails to reach target | no surveillance/ no functional defeat | Axle breaks | 4 | 1 | 7 | 0.6 |

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## FMEA Top 6 Addressed in Analysis Plan

Failure Mode and Effects Analysis (FMEA) Worksheet

| System, Product, or Process: | Pipe Snake | | | | | | |
|---|---|---|---|---|---|---|---|
| Background | | | | Rating | | | |
| Description | Potential Failure Mode | Potential Effect of Failure | Root Causes | SEV | OCC | DET | RPN |
| Deployment | fails to reach target | no surveillance/ no functional defeat | Unable to overcome obstacle | 8 | 6 | 4 | 12 |
| Deployment | fails to reach target | no surveillance/ no functional defeat | Batteries Die | 8 | 5 | 4 | 10 |
| Comm | Loses Comm | no surveillance/ control | Signal Strength not strong enough | 7 | 4 | 3 | 9.3 |
| Deployment | fails to reach target | no surveillance/ no functional defeat | Electronics fail | 9 | 3 | 3 | 9 |
| Deployment | fails to reach target | no surveillance/ no functional defeat | Discovered by enemy | 7 | 5 | 4 | 8.8 |
| Deployment | fails to reach target | no surveillance/ functional defeat | Treads (Prongs) Break | 9 | 2 | 3 | 6 |

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## Pipe Snake Analysis Plan

| Failure or performance mode | RPN | Approach: analytical, simulation or prototype test | Faculty who signed off | Cadet(s) responsible | Due date | New RPN |
|---|---|---|---|---|---|---|
| Unable to overcome obstacle | 12 | Analytical – Flow analysis of fluid going through the pipe | Capt Carroll | Chris | 4-Feb | 3 |
| Unable to overcome obstacle | 12 | Analytical – Determine friction coefficient and determine normal force required | Capt Knauf | Chris | 4-Feb | 3 |
| Unable to overcome obstacle | 12 | Prototype – Find max bend vehicle can handle using pipe snake | Mr. Rodine | Marko | 4-Feb | 3 |
| Batteries die | 10 | Analytical – Determine run-time of a lipo battery given energy consumption | Capt Wahlquist | Kelsey | 4-Feb | 4 |
| Signal strength not strong enough | 9.33 | Analytical - Determine length of pipe before losing communication signal | Capt Branchflower (EE) | Ryan | 4-Feb | 1.8 |
| Electronics fail | 9 | Analytical – Determine typical dud rates of electronics used | Capt Wahlquist | Chris | 4-Feb | 5 |
| Discovered by enemy | 8.75 | Brainstorm – Mission confined to sewage pipes | Dr. Jensen | All | 4-Feb | 1 |
| Treads (Prongs) break | 6 | Analytical – Stress test to determine the force on the legs of the vehicle that will cause failure | Dr. Wood | Kyle | 4-Feb | 2.8 |

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## Sewage Flow Analysis

- Flow of wastewater through the pipes may be an issue
  - Drag
  - Component damage
  - Blockage
- Wastewater properties:

| Properties (Looked Up/Assumed) | | Properties (Calculated) | |
|---|---|---|---|
| Density (kg/m^3) | 850 | Mass Flow Rate (kg/s) | 0.43 |
| Vol. Flow Rate (m^3/s) | 0.00050 | Pipe Cross Section (m^2) | 0.0045 |
| Kinematic Viscosity (m^2/s) | 0.0000013 | Dynamic Viscosity (kg/m/s) | 0.0011 |
| Pipe Diameter (m) | 0.076 | Velocity of Sewage (m/s) | 0.11 |
| Volumetric Flush Rate for 3 toilets flushing (m^3/s) | 0.0030 | Velocity During Flush (m/s) | 0.77 |
| Flush Duration (s) | 6 | Approximate Frontal Area (m^2) | 0.0013 |

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## Sewage Flow Analysis

- Volumetric flow per flush and constant average volumetric flow, determined the highest velocity (and therefore drag) the robot would face
- Approximated a frontal area of impact

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## Sewage Flow Analysis

- Determined force of drag
  - Assumptions:
    - $C_d$ similar to that of a cone
    - 1.4 gal per 6 second flush volumetric flow rate and 3 toilets flushing, in addition to a steady flow rate of 0.132 gal/s
    - Contact area of 2 $in^2$
- Results:

| C_d | Drag (N) | Drag (lbf) |
|---|---|---|
| 0.50 | 0.16 | 0.04 |

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## Coefficient of Friction Analysis

- Team needed a coefficient of friction for rubber against PVC material
  - Allows team to determine normal force for robot to climb through vertical pipe for a given mass
- Analytical tests performed under wet and dry PVC surface conditions

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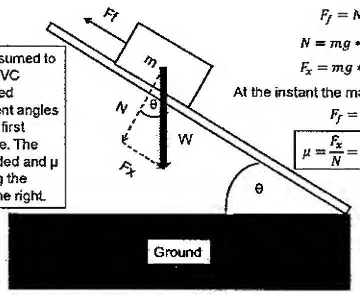
## Test Setup (Coeff. of Friction)

Plexiglass (assumed to be similar to PVC material) is lifted through different angles until the mass first begins to move. The angle is recorded and μ is solved using the equations to the right.




$F_f = N * \mu$

$N = mg * \cos(\theta)$

$F_x = mg * \sin(\theta)$

At the instant the mass first moves:

$F_f = F_x$

$\boxed{\mu = \frac{F_x}{N} = \tan(\theta)}$



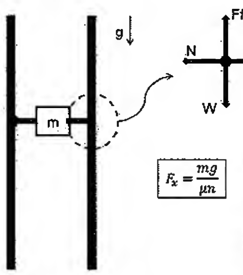
## Coefficient of Friction Analysis

- 3 tests run with dry surface
- Team slathered mud onto the Plexiglass surface to simulate wet conditions
- 3 tests run with wet surface
- Average coefficient of friction determined for each condition
- Results

| Coeff. Static Friction | Dry | Wet |
|---|---|---|
| Test 1 | 0.68 | 0.46 |
| Test 2 | 0.70 | 0.51 |
| Test 3 | 0.71 | 0.51 |
| Average | 0.70 | 0.49 |



## Force Applied on Wall per Contact Point




$\boxed{F_x = \frac{mg}{\mu n}}$

$F_x = N$

$F_f = N * \mu$

$F_f = W = \frac{mg}{n}$

where $n = \#\ of\ points\ of\ contact$

$F_x = force\ against\ wall\ per\ point\ of\ contact$

$\mu = static\ coefficient\ of\ friction$

| | Results for 1kg mass | Dry | Wet |
|---|---|---|---|
| mass of robot (kg) | n (# of legs against wall) | Force req'd per leg (N) | |
| 1 | 3 | 4.7 | 6.6 |
| gravity (m/s^2) | 4 | 3.5 | 5.0 |
| 9.81 | 5 | 2.8 | 4.0 |
| | Results for 1 lbm mass | Dry | Wet |
| mass of robot (lbm) | n (# of legs against wall) | Force req'd per leg (lbf) | |
| 1 | 3 | 0.48 | 0.68 |
| gravity (ft/s^2) | 4 | 0.36 | 0.51 |
| 32.17 | 5 | 0.29 | 0.41 |



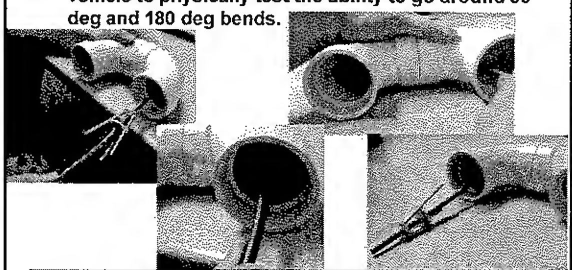
## Chassis Size/Weight

| Component | Number | Weight of 1 (lb) | Total (lb) | Volume of 1 (in^3) | Total (in^3) |
|---|---|---|---|---|---|
| Prong | 6 prongs | 0.067 lb/prong | 0.405 | 0.05 $in^3$/prong | 0.33 |
| Pipe Snake | 1 foot | 0.112 lb/ft | 0.112 | 2.36 | 2.36 |
| Servos | 3 servos | 0.045 lb/servo | 0.134 | 0.32 | 0.64 |
| Batteries | 1 battery | 0.269 lb/battery | 0.269 | 3.81 $in^3$/battery | 3.81 |
| Payload | 3 | 1 | 3 | 1 | 3 |
| Total | 14 parts | 1.57 lb | 3.92 lb | 10.35 $in^3$ | 12.95 $in^3$ |



## Cornering/Flexibility

- Used the pipe snake and an improvisation of the vehicle to physically test the ability to go around 90 deg and 180 deg bends.





## Other Considerations

- Other obstacles
  - 3-way intersection
  - Blockage
  - Signal/communication wire breaks
  - Power wire breaks
- Solutions
  - Remote controlled turning capability
  - Ability to backup
  - Drive forward until stopped
  - Self destruct when no power

## Battery Life

- Using 1 standard and 2 micro servos
  - One servo operates at a time
  - Avg loaded current = 940/3 = 313.3 mA
  - Avg idle current draw = 20.3/3 = 6.77 mA
  - Assume 8 hours movement / 16 hours idle
- Battery Capacity (Ah) = Current x Time
  - Battery Capacity =
    (313.3 mA)(8hrs) + (6.77 mA)(16hrs) = 2615 mAh
- G6 ProLite 25C Series LiPo Batteries
  - TP2700-2SPL25: 2700 mAh / 2-cells / 0.269 lbs / 3.81in³ (8 hour run time)
  - TP1350-2SPL25: 1350 mAh/ 2-cells / 0.141 lbs / 1.92 in³ (4 hour run time)

| | Max current | Idle Current |
|---|---|---|
| Parallax Futaba Standard Servo (x1) | 140±50 mA | 15 mA |
| HS-56HB Sub-Micro Servo (x2) | 400±100 mA | 5.3 mA |
| Total current drawn | 940 mA | 20.3 mA |

- Alternatively - Tether to deliver power using same cable as communication

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## Operational Range

- Cables were analyzed based off of research done from various websites. www.hyperline.com provided dimensions and weight per 1000 feet.

| Type of Cable | Diameter | Transmission Length | Weight per 1000 feet |
|---|---|---|---|
| RG-59 | 0.81 mm | 600 feet | 23.59 lbs |
| RG-6 | 1.02 mm | 1000 feet | 30.9 lbs |
| CAT-5 | 0.5 mm | 3000 feet | 12.2 lbs |
| Fiber Optic (Single Mode) | 0.125 mm | Up to 40 miles | 33.60 lbs |

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## Electronic Equipment Fails

- Possibility of electronics failing before utilization (dud)
  - Dud/failure rates researched for typical consumer electronic products
  - Found to be <3%, therefore can be neglected

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## Brainstorming

- Alternate missions that allow vehicle to remain hidden in pipes
  - Block pipes
  - Deploy smaller robots
  - Map sewer system
  - Release tear/poison gas
  - Explode
  - Sample sewage matter
  - Drivetrain to drive out of sewer and into bunker
  - Listen/spy on conversations
  - Electromagnetic/vibrational sensor (find mechanical rooms)
  - Radioactive → poison them

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## Mission Selection

- Considerations for down selection
  - Ability to stay hidden
    - Small size
    - Quiet
    - Remain in sewer pipes
  - Usefulness
    - Sampling sewage and blocking pipes not as useful
    - Electromagnetic sensors could be used to find key areas of enemy activity
    - Explode – ability to defeat an enemy function
  - Cadet ability to build
    - Already very small – cannot deploy smaller bots

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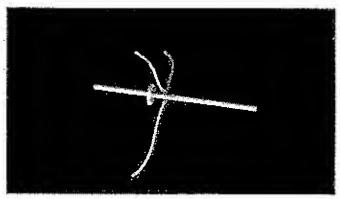
## SolidWorks

- Proposed design
  - Map sewer system
  - Electromagnetic sensing
  - Explode!



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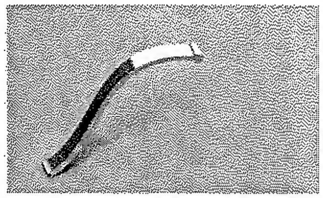
## FEA Stress Analysis

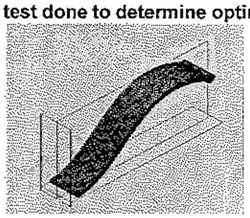
- FEA Stress Analysis in SolidWorks
  - Used ABS Plastic for easy prototyping





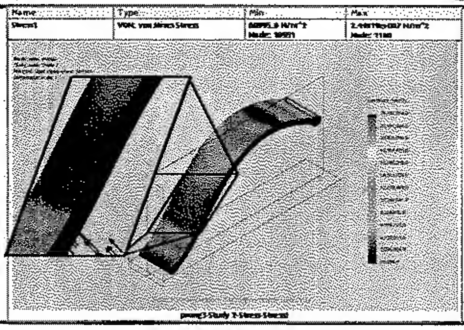
## FEA Stress Analysis

- Meshed using tetrahedral elements
  - 11,098 elements
  - Very fine mesh
- Convergence test done to determine optimal mesh quality





## FEA Stress Analysis





## FEA Stress Analysis

- Prong can hold load of 17.79 N (4.0 lb) with a FS = 1.63
  - Based on failure due to yield at $4.007 * 10^7 \frac{N}{m^2}$
- This model was verified by hand analysis



## Alternate Version

| Root Causes | SEV | OCC | DET | RPN | Owner | Due/Done | Action | SEV | OCC | DET | RPN |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Unable to overcome obstacle | 8 | 6 | 4 | 12 | Chris/ Marko | February | Analysis of flow, friction, and force | 8 | 3 | 8 | 3 |
| Batteries Die | 8 | 5 | 4 | 10 | Kelsey | February | Analyze batteries | 8 | 3 | 6 | 4 |
| Signal Strength not strong enough | 7 | 4 | 3 | 9.3 | Chris | February | Signal cable analysis | 9 | 2 | 10 | 1.8 |
| Electronics fail | 9 | 3 | 3 | 9 | Chris | February | Statistical analysis | 5 | 1 | 1 | 5 |
| Discovered by enemy | 7 | 5 | 4 | 8.8 | All | February | Brainstorm ideas | 7 | 1 | 7 | 1.0 |
| Legs Break | 9 | 2 | 3 | 6 | Kyle | February | FEA stress analysis | 8 | 1 | 8 | 1 |



## Overview of Budget

| Object Purchased | Location Purchased | Price+Shipping | Date | | Total Spent |
|---|---|---|---|---|---|
| Igniter | Hobbylinc | $26.56 | 1-Nov-12 | | $260.38 |
| LaunchPad | Amazon | $23.90 | 11-Jan-13 | | |
| LiPo | Amazon | $43.91 | 15-Jan-13 | | |
| Micro Fish Hooks | Tenkarabum | $23.00 | 12-Dec-12 | | Prototype Budget |
| Piping | Lowes | $31.88 | 12-Dec-12 | | $10000 |
| RC Car | Amazon | $46.00 | 26-Nov-12 | | |
| Wireless Transciever | SparkFun | $17.54 | 11-Jan-13 | | |
| Velcro Tape | Amazon | $8.96 | 1-Nov-12 | | Remaining Budget |
| Micro Camera | Amazon | $24.51 | 17-Jan-13 | | $9739.62 |
| Drain Auger | Home Depot | $14.12 | 22-Jan-13 | | |

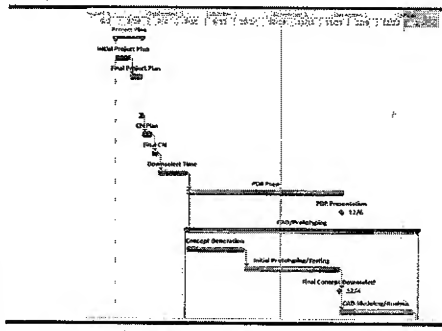
| | | | |
|---|---|---|---|
| Cadet travel to Eglin AFB | 1000 | 8 | 8000 |
| Faculty travel to Eglin AFB | 1500 | 3 | 4500 |
| Travel Budget Remaining | | | 12500 |

## Project Forecast

- Pellet
  - Finalize launcher
  - Complete stand-alone igniter system and upgrade
  - Integrate all components
  - Remote control of system
- Pipe Snake
  - Finish CAD modeling
  - Build initial prototype
  - Figure out electronics
  - Test and improve prototype

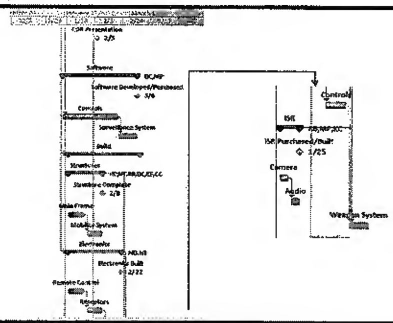


## Schedule: Gantt Chart



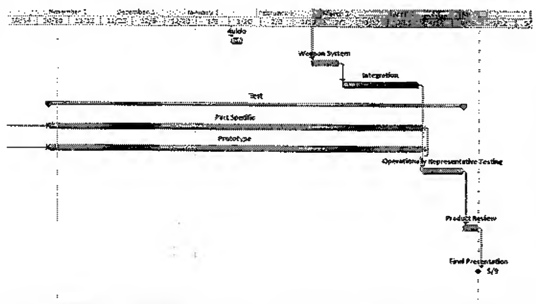


## Schedule: Gantt Chart





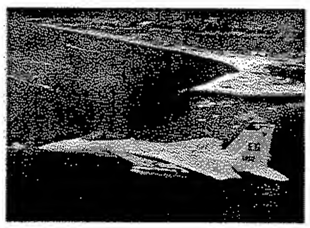
## Schedule: Gantt Chart





## Scheduled Sponsor Briefs

- Sponsor brief at Eglin AFB, Florida
  - Tentatively 29 April 2013
  - AFRL
  - DTRA
  - JGRE





## Questions?

# Appendix



# Drop test

| | | | | g (ft/s^2) |
|---|---|---|---|---|
| | | | | 32.170 |

| Body Part | Height Dropped (ft) | speed on impact (ft/s) | speed on impact (m/s) | time during fall (s) |
|---|---|---|---|---|
| shoulder/upper back | 0.58 | 6.13 | 1.87 | 0.190423642 |
| lower back | 1.00 | 8.02 | 2.45 | 0.249223072 |
| thigh | 1.00 | 8.02 | 2.45 | 0.249223072 |
| boot | 2.00 | 11.34 | 3.46 | 0.3525[illegible] |

| | | mass (paintball) (g) | mass (paintball) (lb) |
|---|---|---|---|
| | | 3 | 0.00661 |
| Body Part | Height Dropped (m) | Impacting Momentum (kg-m/s) | Impacting Momentum (kg-m/s) |
| Shoulder/Upper Back | 0.18 | 0.0056 | 0.04 |
| Lower Back | 0.30 | 0.0073 | 0.05 |
| Thigh | 0.30 | 0.0073 | 0.05 |
| Boot | 0.61 | 0.0104 | 0.07 |

Determine launching force

| Drag coefficient of sphere | delta t (s) | density air (lb/ft^3) | A (ft^2) | mass |
|---|---|---|---|---|
| 0.47 | 0.01 | [illegible] | [illegible] | 0.00661 |

| Time | F (drag) (lbf) | Vf (ft/s) | Vi (ft/s) | Vf (m/s) | momentum (ft-lb/s) | momentum (kg-m/s) |
|---|---|---|---|---|---|---|
| 0 | 0.0232075e02 | 6.12664[illegible] | 6.12664[illegible] | 1.867[illegible] | 0.040497[illegible] | 0.00554[illegible] |
| 0.01 | | [illegible] | [illegible] | 1.867[illegible] | [illegible] | [illegible] |
| 0.02 | | [illegible] | [illegible] | 1.867[illegible] | [illegible] | [illegible] |
| 0.03 | | [illegible] | [illegible] | 1.867[illegible] | [illegible] | [illegible] |
| 0.04 | | [illegible] | [illegible] | 1.867[illegible] | [illegible] | [illegible] |
| 0.05 | | [illegible] | [illegible] | 1.867[illegible] | [illegible] | [illegible] |
| 0.06 | | [illegible] | [illegible] | 1.867[illegible] | [illegible] | [illegible] |
| 0.07 | | [illegible] | [illegible] | 1.867[illegible] | [illegible] | [illegible] |
| 0.08 | | [illegible] | [illegible] | 1.867[illegible] | [illegible] | [illegible] |
| 0.09 | | [illegible] | [illegible] | 1.867[illegible] | [illegible] | [illegible] |
| 0.1 | | [illegible] | [illegible] | 1.867[illegible] | [illegible] | [illegible] |
| 0.11 | | [illegible] | [illegible] | 1.867[illegible] | [illegible] | [illegible] |

# Executive Summary

**Unmanned Robotic Infiltration Team**
**United States Air Force Academy**
**David Carte & Kyle Fitle**

## Overview

Most military adversaries of the United States prefer operating from what are known as Hard and Deeply Buried Target (HDBT). HDBTs such as caves or bunkers offer protection and concealment from attack and surveillance. In order to pursue and protect national security objectives and interests, it is desirable for the United States military to both gather information about operations within these HDBTs and have the possibility to functionally defeat one or more of their capabilities. For deployed special operations forces, infiltration of a hard and deeply buried target is both difficult and fraught with danger. Customer needs gathered from the Defense Threat Reduction Agency (DTRA), the Joint Ground Robotics Enterprise (JGRE), and the Air Force Research Labs (AFRL) led to the development of a concept of operations for the system's utilization. Two systems have been selected to attack the issue of infiltration and functional defeat of an HDBT; a sewer-pipe infiltration robot known as the "pipe snake" and an adhesive pellet projectile system (APP). The sewer-pipe robot will utilize the often overlooked sewage systems to infiltrate HDBTs. The pellet projectile will attach to personnel entering the HDBT and will have the ability to incapacitate personnel or gather information and intelligence.

## Concept 1

The pipe snake depends on the assumption that the HDBT has some type of pipe system for sewage and waste removal. The pipe snake will infiltrate through sewage pipes using a system of expanding and collapsing legs to push and extend its way through the pipes. The pipe snake consists of two segments connected by a flexible shaft. As the legs of the back segment expand against the pipe walls, the forward segment will slide forward. The legs of the forward segment will then expand, holding the robot in place and allowing the back segment to follow. This legged design allows the sewer pipe robot to maintain a greatly reduced frontal surface area. A lower frontal area will enable it to address variable pipe diameters, be more resistant to fluid drag, and pass through obstacles such as a chain-link fence within the pipe. The flexible shaft will allow for maneuverability through corners and other bends within a sewer system. This robot will contain various intelligence, surveillance, and reconnaissance (ISR) sensors that will enable it to gather valuable information about the layout of the HDBT as well as determine the location of electronic activity.

## Concept 2

The APP system consists of miniature pellet units that resemble cockleburs. Launched from a pneumatic system that will be disguised and placed within the proximity of the HDBT, these pellets will adhere to the clothing of personnel and equipment entering the HDBT using tiny hooks on the surface of the pellet. The payload can be an incapacitating agent to affect personnel, or can be ISR sensors that gather valuable intelligence about operations within the HDBT. As a functional defeat capability, kinetic effects such as flash bangs, tear gas, or explosives can be used. Accelerometers could be used to map the overall layout of the HDBT as well as determine highly-visited areas or paths. Since the concept aims to attach pellets to as many individuals as available, it may be possible for each pellet to act as a relay point from which information is eventually transmitted out of the HDBT. These payloads will communicate and be activated remotely.

## Conclusion

The systems will be operated by US Special Forces. Minimal training would be required to operate the system. Special Forces are continually concerned about weight and size of the objects that they carry. For this reason it is important that the size and weight are kept to a minimum and that everything the prototype does is useful in completing the mission.

The cost of the vehicles ranges between \$100 – \$2000, with variability based on materials used for its construction and operational lifetime desired. While alternative systems exist, none are capable of accomplishing the needed task without putting lives in danger or creating damage. This team will create initial prototypes of both the Pipe Snake and APP. Continued research and development is required to make these systems effective in real-world scenarios. The design could then be further iterated on the Air Force Research Labs (AFRL), the Defense Threat Reduction Agency (DTRA) and the Joint Ground Robotics Enterprise (JGRE) using their expertise in the matter.

# Innovative Solutions Against Hard and Deeply Buried Targets

TEAM MEMBERS: Dave Carte, Kyle Fitle
Team Advisor: Capt Joseph Wahlquist
SCHOOL: US Air Force Academy

## Introduction

Most military adversaries of the United States prefer operating from what is known as a Hard and Deeply Buried Target (HDBT) such as a cave or bunker due to the protection and concealment from attack and surveillance these installations offer. Infiltration of these bunkers is both difficult and fraught with danger. In order to pursue and protect national security objectives and interests, it is desirable for the United States military to both gather information about operations within these HDBTs and have the possibility to functionally defeat one or more of their capabilities.

Two systems have been selected to attack this issue from widely varying directions. These two concepts include a sewer-pipe robot known as the "pipe snake" and an adhesive pellet projectile system (APP). The sewer-pipe robot will utilize the often overlooked sewage systems of HDBTs, based on facility visits inside the United States. The pellet projectile will be attached to personnel entering and leaving the HDBT and can incapacitate personnel or gather information and intelligence while attached to the personnel.

## Technical Analysis

While HDBTs are inherently well-defended and difficult to infiltrate, they are not invulnerable to penetration. The various avenues of infiltration that have been identified are as follows: power cables, entrances/exits for personnel and equipment, air intakes/exhausts, diesel combustion intakes/exhausts, water utilities, and waste removal. Analysis and research has illuminated the difficulty of infiltration by many of these methods due to the existence of built-in defense characteristics such as blockades or incredibly small maneuvering space. It was determined that the most effective ways to infiltrate an HDBT are with personnel or through the sewer pipes. The first option rests on the overarching rationale that if a human can fit through an entrance a disguised system can as well. The viability of the second option was confirmed during a trip to Fort Hood when officials confirmed that their own sewer system was largely ignored and unmonitored. Customer needs gathered from the Defense Threat Reduction Agency (DTRA), Joint Ground Robotics Enterprise (JGRE), and Air Force Research Labs (AFRL) led to the development of the following concept of operation for the system's utilization: initial deployment from forward operating Special Forces personnel, infiltration of the robot into the HDBT, navigation to the critical location, defeat of a critical target function, and possible exfiltration.

The APP system relies on the concept of miniature pellet units (concept size is roughly that of a paintball) that resemble cockleburs through the employment of tiny hooks on the surface of the pellet (Figure 1). Launched from a pneumatic system that will be disguised and placed within the proximity of the HDBT, these pellets will adhere to the clothing of personnel and equipment entering the HDBT. Our prototyping goal is to develop a miniature controller to communicate with the pellets which could contain a variety of different payloads. The payload can be some incapacitating agent that will affect personnel, or intelligence, surveillance, and reconnaissance (ISR) sensors that will gather valuable intelligence about operations within the HDBT. As a functional defeat capability, kinetic effects such as flash bangs, tear gas, or explosives can be used in conjunction with infiltration by Special Forces personnel to aid them in securing the HDBT if needed. Another example is using accelerometers to map the overall layout of the HDBT as well as determine highly-visited areas or paths. Since the entire system aims to attach multiple pellets to as many individuals as available, it may be possible for each pellet to also act as a relay point from which information is eventually transmitted out of the HDBT or to US Special Forces members infiltrating the HDBT. These payloads will communicate and be activated remotely.

While the current design sits at approximately 1.6" in diameter, the final product would be 0.5" in diameter or smaller while containing a complete control system (microcontroller, battery, transceiver, and igniter) in the space without any more than perfunctory integration. The actual size of the pellet is limited mainly by the payload required for a desired mission (ie: a particular amount of explosives is needed). The passive current draw of the system allows for over 2 years. The expected use would involve higher current draws for a shorter period of time. For example, if an accelerometer were used, the current draw (~350 microamps) would be far higher (several orders of magnitude).This would only allow for several days of operation instead of years, but still sufficient time for deployment and operation within the HDBT.

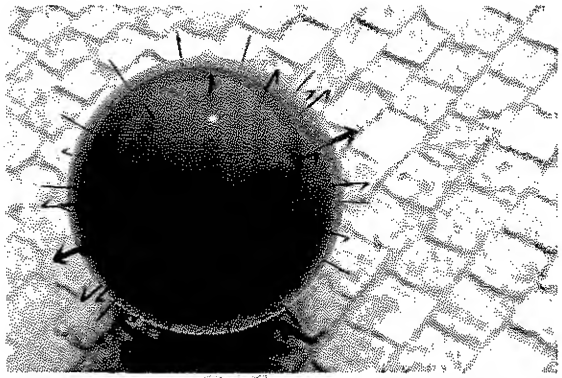


**Figure 1: Close-up concept picture of the pellet unit from the adhesive pellet projectile system.**

The pipe snake will infiltrate through a sewer pipe system using a system of expandable and collapsible legs that will use friction force on the walls of the pipe to push and extend its way through the pipe system. Seen in Figure 2, the pipe snake consists of two segments connected by a flexible shaft. As the legs of the back segment expand and create friction against the pipe walls, the forward segment will slide forward. The legs of the forward segment will then expand, holding the robot in place and allowing the back segment to follow. This legged design, as opposed to the common design using wheels, allows the sewer pipe robot to maintain a greatly reduced frontal surface area. A lower frontal area will enable it to address variable pipe diameters more effectively, be more resistant to fluid drag, and pass through obstacles such as a chain-link fence within the pipe. The flexible shaft will allow for maneuverability through corners and other expected bends within a sewer system. This robot will contain various ISR sensors that will enable it to gather valuable information about the layout of the HDBT as well as determine the location of electronic activity.

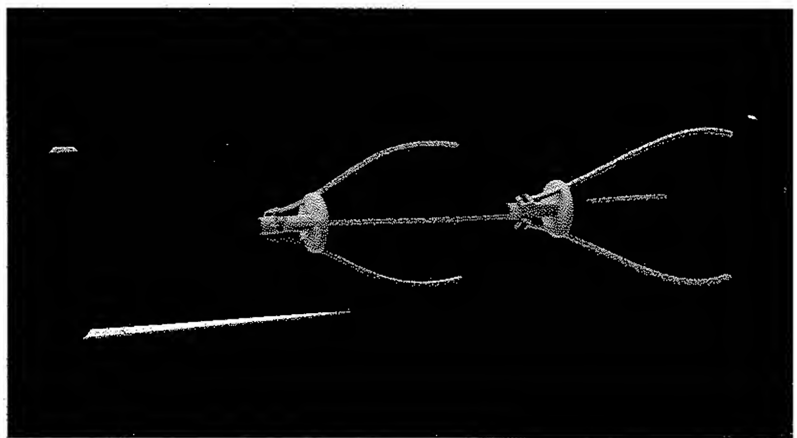


**Figure 2: CAD model of pipe snake.**

After determining the APP and the sewer pipe snake to be the most innovative, feasible, and useful design concepts, analysis was done to determine the most common methods of failure for each system. Once these common means of failure were identified, further analyses were performed to determine ways in which failure could be prevented through superior production and manufacturing. Possible methods of failure for the APP included: hooks not sticking to the target, system being too easy to remove from the target, system not having the proper timing controls and activating at an improper time, igniter not working properly, electronics failing, and the gas inside being ineffective.

To satisfy the customer that the APP system will not fail in any of these manners, several analyses were performed. The APP system was prototyped using a ping pong ball and small hooks. It was determined that the system sticks very well and is difficult to remove from certain locations of the body such as the back. Additionally, it was difficult for the test subject to feel the projectile hit his body in certain areas such as boots and loose fitting clothing. The device that will ignite the contents of the APP, either explosives or an incapacitating agent, has also been prototyped and proved that it will detonate when activated. The timing system for the igniter has been tested to a limited extent, but further research is being done on how to communicate with the device so that it can intelligently carry out the mission to incapacitate or defeat capabilities rather than just being a dumb bomb. It was determined analytically that the system, with a proposed diameter of 0.5 inches, will be able to carry enough of an explosive substance to incapacitate the person that is carrying it. Lastly, the use of multiple adhesive pellets will ensure that even if one or several fail, there will still be many functional

pellets in use that can defeat the capabilities of the HDBT and allow the effective entry and success of Special Operations Forces personnel.

Possible modes of failure for the pipe snake included: inability to overcome an obstacle, loss of power, loss of signal, electronic failure, discovery by enemy, and legs breaking due to the stresses on the system. Many analyses were conducted on the pipe snake system as well and are contained in the following paragraphs to satisfy the customer that the pipe snake will not fail by the methods identified.

The largest area of concern was that the pipe snake would not be able to overcome obstacles within the pipes. Based upon the knowledge that sewage pipes may climb vertically at points in the system, it became clear that the sewer-pipe snake will likely have to climb straight up in order to perform its function. This would require a normal force, and hence friction force, being placed against the sewer pipe walls. The team recognized that a coefficient of friction between the robot arms and the sewer walls would need to be considered. Tests were run to determine the coefficient of friction for a common piping material, PVC. This coefficient of friction was coupled with the concept of self-exciting and self-locking brakes [Juvinall]. Essentially, a particular angle between the legs and the wall can be determined such that an additional force pushing the robot backwards increases the friction force by an amount greater than the pushing force. In this configuration, the robot will not slide backwards down the pipe, thereby allowing it to withstand a large amount of pushing force and allow it to climb vertically [See Figure 3].

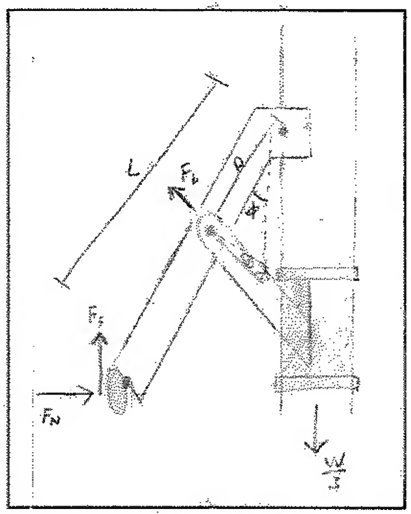


**Figure 3: Determination of self-locking angle**

Another obstacle that the pipe snake will surely encounter is bends in the pipe to include 180 degree bends and S bends. A max bend analysis was performed that included a rough prototype of the system. The prototype consisted of the flexible material intended for use as the shaft of the system and legs glued on in approximately the proper position. The pipe snake was in fact able to navigate the 180 degree bend in the pipe with minimum extra force applied.

In traversing the sewage pipes of a hard and deeply buried target, the pipe snake system is guaranteed to encounter drag forces from the flow of the sewage matter away from the facility. Although disgusting to think about, the pipe snake must be able to hold its ground against a barrage of water and waste! This observation led the team to the Air Force Academy's resident wastewater engineering professional, Dr. Phelan. Through discussions with Dr. Phelan, the team began an analysis utilizing Manning's equation to estimate the pipe diameter and determine a typical velocity the robot would encounter in the sewer pipes. Through research, and an estimate of approximately 1500 people in the target HDBT, it was determined that a 1 foot diameter pipe would be likely for the mainline in the system and a typical usage of forty gallons per person per day would be a conservative assumption because the actual usage would likely be less than this [Davis and Metcalf]. Using these assumptions, the depth of sewage in the mainline pipe was determined to be approximately 3.3 inches, or 27.5% of the total pipe depth, with a velocity of 4.7177 feet per second. This is a conservative average, calculated for peak hours in the day for water usage.

One more potential failure mode was loss of power to the system. After much discussion and consideration of added weight versus available power, it was decided that the team would use lithium polymer batteries to power the sewer-pipe robot. Using a G6 ProLiet 25C Series LiPo battery (TP2700-2SPL25: 2700 mAh / 2-cells / 0.269 lbs / 3.81 in$^3$), the robot would have an 8 hour run time. Another potential failure mode was that the system would lose communication because the signal strength is not strong enough. For

the infiltration of a hard and deeply buried target, it is assumed that wireless communication with the system will not be available. The system could be connected using cables such as fiber optic cables or it could be autonomous. Although using fiber optic cables would not add much weight to the system, it was decided that cables would not be used because of the potential for them to break, which would leave the robot stranded. For this reason the pipe snake will be made autonomous programmed with a microcontroller. One option for receiving information gathered by the pipe snake consists of the ability to drop small relay signal pucks that will transmit data along the course the pipe snake has passed and eventually to US military operators.

Although further prototyping remains to be done, initial prototypes have shown great potential for both the APP and sewer pipe systems. The initial prototype of the adhesive pellet utilized a Ping-Pong ball to provide a small hollow shell to which miniature fishhooks were attached to provide a way for the pellet to adhere to clothing. A timing circuit was used to provide the ignition to of the substance inside of the hollow shell. Adhesion results were very effective; on impact, the hooks held extremely well to clothing. Ignition using a capacitor is simple and also proved possible. Currently, the ability to miniaturize the concept is limited due to the limited ability to construct nanotechnology. However, the team has verified viable elements of the system which can later be scaled down in the final production. Prototyping of the pipe snake thus far consists of the rough design used for the bending test as well as detailed schematics and movement characterization using SolidWorks.

**Operational Needs**

The prototypes created will be operated by US Special Forces. Minimal training would be required to operate the system. Special Forces are continually concerned about weight and size of the objects that they carry. For this reason it is important that the size and weight are kept to a minimum and that everything the prototype does is useful in completing the mission. At the moment, estimates for the APP system as well as the pipe snake tally in at around 5 lb each.

**Implementation Readiness Analysis**

**Market Analysis**

Prototype costs depend mainly on the kind of function either one is intended to perform. To continue to miniaturize the adhesive pellet projectile for example, a timing circuit board no larger than a hand watch would be required along with a launching mechanism. Depending on the size of the final pellet and precision of the launching mechanism, the final cost of the product ranges between a couple of hundred to a few thousand dollars. The sewer bot would likely be an automated system and therefore the cost could rise substantially due to specific functions it might need to perform – for example, a small sound recording device costs much less than development and implementation of specialized tooling for piping manipulation purposes. As such, cost is driven largely by the sort of functional attachments desired or required on the vehicle. The cost of the vehicle ranges between $100 – $2000, with variability based on materials used for its construction and operational lifetime desired. With our customer being the Department of Defense and with developing this while working for the Air Force, no profit will be made with this project.

While alternative systems exist, none are capable of accomplishing the needed task without putting lives in danger or creating damage causing death or injury. Current systems such as bunker busting bombs and specially trained soldiers are also incapable of covert operations and are far more expensive and valuable than the sewer bot or adhesive pellet projectile. While there are currently available systems that are capable of traversing sewage pipes – although none are known that are capable of navigating autonomously through bends or operating in variable diameter piping – adhesive pellets do not exist. With the innovative technology of each of these, design patents would be pursued to protect the ideas. The design could then be further iterated on by DTRA and JGRE using their expertise in the matter.

**Industry Analysis**

For the pipe snake, the chassis is required to be flexible to accomplish the mission. To make it flexible, a shaft such as what drain cleaners are built out of will be one alternative. Another alternative would be to create the chassis using a flexible steel catheter material. This would provide high tensile and compressive strength while still providing flexibility. The legs and other key components of the pipe snake will be rapid prototyped, but could also be machined with careful precision. Although large scale production is a useful tool in decreasing cost, it will not be necessary in this situation as it is highly unlikely that a mass quantity of these bots will be produced.

The adhesive pellet projectile will likely be constructed using aluminum that will be shaped into a pellet of about ½ inch in diameter. To attach an adhesive mechanism on this pellet will require an unconventional form of production as it is likely that several small fish hooks will be attached. Multiple pellets (10-20) will be produced to allow the prototype to adequately demonstrate its concept of operations.

**Recommendations**

Continued research and development is required to make these systems effective in real-world scenarios. This team will continue fine-tuning prototypes using the given prototyping and testing budget of $10,000. Due to the lack of time, funding, and team skill, the best option for this project will be to pass it on to professional research organizations to miniaturize and streamline the prototypes, creating final products which accomplish the desired mission. This team will have functional prototypes which will demonstrate the concepts of operation built and tested by 20 April 2013. These prototypes will then be demonstrated to the sponsors and the innovations and technology passed to them for further development. The current sponsoring organizations would be ideal for this plan. Therefore, the current designs will be prototyped to the best ability of this team, and then the prototypes will be passed to the Air Force Research Labs (AFRL), the Defense Threat Reduction Agency (DTRA) and the Joint Ground Robotics Enterprise (JGRE).

**References**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Metcalf and Eddy, Inc. (2003). *Wastewater Engineering: Treatment and Reuse*, 4th Ed., McGraw-Hill Inc., New York.

Juvinall, Robert C., and Kurt M. Marshek. *Fundamentals of Machine Component Design.* Hoboken, NJ: John Wiley & Sons, 2011. Print.

# HDBT Defeat

**Unmanned Robotic Infiltration Team**
United States Air Force Academy

## Mission

The purpose of this project was to develop an innovative system to infiltrate and defeat the capabilities of a hard and deeply buried target (HDBT) such as a bunker or cave system.

## Concept of Operations

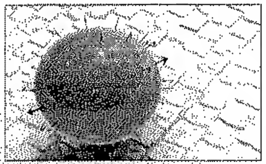
- Deploy unit 500yd outside HDBT
- System infiltrates HDBT
- Locates and maneuvers to target area
- Performs ISR
- Deploy functional defeat methods within 24 hours of drop-off

Initial Deployment → Infiltration → Navigate to Critical Area → Defeat Target → Exfiltration (if possible)

## Sponsors and Users

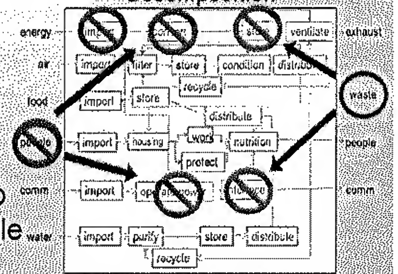
- Air Force Research Labs
- Defense Threat Reduction Agency
- Joint Ground Robotics Enterprise
- Special Operations Forces

## Concept 1: Pellet

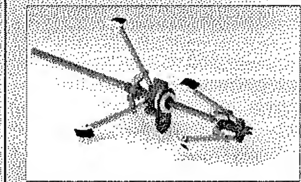


- Small in size: ~0.5 in diameter
- Launched from pneumatic system
- Attach to personnel/equipment with miniature hooks
- "Hitch ride" into the HDBT
- Conduct surveillance

HDBT Functional Decomposition



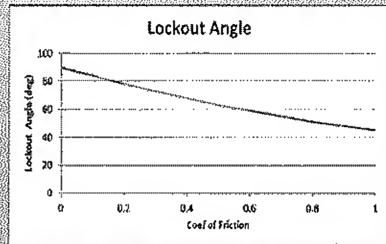

## Concept 2: Pipe Snake

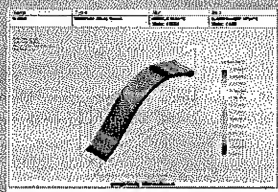


- Robot infiltrates HDBT through sewer pipe system
- Designed to navigate bends, climb vertically, and maneuver in variable diameter pipes
- ISR capabilities: map sewer system,

## Technical Analysis and Testing

- Determination of "self-locking" leg angle of pipe snake based on coefficient of friction
- Battery and operability life
- Critical failure analysis of potential failure modes
- Pellet ignition and adhesion



- Prong can hold load of 17.79 N (4.0 lb) with a FS = 1.63
  - Based on failure due to yield at $4.007 \cdot 10^7 \frac{N}{m^2}$
- This model was verified by hand analysis